X-Ray Detection of an Obscured Active Galactic Nucleus in a $z = 3.09$ Radio-quiet Lyα Nebula

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ABSTRACT

We present evidence for a highly obscured X-ray source in one of two giant Lyα emission nebulae in the $z = 3.09$ proto-cluster region SSA22. Neither Lyα nebula is associated with significant radio emission. While one has a significant submillimeter detection and is undetected in the X-ray, the other is a factor of 2-10 times less submillimeter bright and appears to contain a hard-band X-ray source. We discuss our analysis and techniques for assessing the X-ray properties of this source and suggest that we have detected an embedded AGN source in one of these nebulae which may be at least partially responsible for exciting the Lyα emission through a mechanism that is essentially decoupled from the radio, submillimeter, or optical luminosities. We also present an upper limit on the mean X-ray emission from 10 other extended Lyα objects in the SSA22 region.

Subject headings: galaxies:high-redshift—galaxies:evolution—galaxies:formation—X-rays:galaxies

1. Introduction

The standard paradigm of structure formation in a universe dominated by cold dark matter suggests that the high-density regions of the high-redshift universe that later collapse

into clusters should also be host to the progenitors of massive galaxies. Identifying both proto-cluster regions and proto-elliptical galaxies therefore offers an opportunity to directly witness the astrophysical phenomena that likely set many of the characteristics of clusters and cluster galaxies seen today.

The identification of protocluster regions at $z > 2$ remains a challenging task. Among the approaches used are the localization of spatial excesses of objects such as Lyman break galaxies (Steidel et al. 1998), Lyman emission line objects (e.g., Hu, Cowie, & McMahon (1998)), and submillimeter sources (e.g., Ivison et al. (2000)), and the apparent correlation of QSO absorption features along adjacent lines of sight (Francis et al. 1996). A slightly different approach involves the use of signpost objects, such as luminous radio galaxies, which are expected to form in the highest density regions at high redshift (Stevens et al. 2003). All of the above methods have yielded positive results with varying degrees of success.

In a survey of continuum-selected Lyman break galaxies Steidel et al. (1998, 2000) have found evidence for a highly significant overdensity of objects at $z = 3.09$ (a factor of ~ 5 higher number density than the average equivalent volume at this redshift). In subsequent narrowband Lyα imaging of this field, two very bright, large, diffuse Lyα-emitting nebulae (or "halos" or "blobs") were discovered. Named "blob 1" (B1) and "blob 2" (B2) by Steidel et al. (2000) these objects have sizes of 17" and 15" (B1, B2), Lyα luminosities of 10^{44} ergs s^{-1}(B1) and 9×10^{43} ergs s^{-1} (B2), and rest equivalent widths of *at least* 370 Å. Both blobs have radio continuum fluxes at 1.4 GHz at least 3 orders of magnitude fainter than those of typical luminous high-redshift radio galaxies (B1 has a tentative radio identification with a 44 μJy [1.4 GHz] source; Chapman et al. (2004)). High-z Lyα halos certainly exist with very powerful radio sources and jets (e.g., van Breugel et al. (2003); Reuland et al. (2003)); however these have been preselected by their radio luminosity, and so it is not clear whether low radio activity is common or not in such systems. submillimeter observations of the blobs have detected sources that (given the $\sim 15''$ half-power beamwidth at 850 μm) are potentially counterparts to B1 and B2 (Chapman et al. 2001, 2004). However, while the B1 counterpart was detected as a 20.1 ± 3.3 mJy source at 850 μm, for B2 the submillimeter emission was significantly less at 3.3 ± 1.2 mJy. Thus, the B1 submillimeter counterpart is one of the most luminous submillimeter high-z sources known, while the B2 counterpart is of low significance.

In recent follow-up work on B1, Chapman et al. (2004) have further identified several optical continuum components (to a limit $R \sim 28.6$) that may be associated with the core of the submillimeter source, and that appear within, and are potentially associated with, the 17" (~ 140 kpc) Lyα blob. They also obtain a marginal detection of a CO(4-3) molecular line and estimate a molecular gas mass of $2 \times 10^{10} M_\odot$. Furthermore, Chapman et al. (2004)

find no significant X-ray emission associated with B1 using deep *Chandra* data, which we further analyze below.

The current physical interpretation of the B1 structure is that it is consistent with an undetected, dust-obscured active galactic nucleus (AGN), together with a starburst region embedded at the core of the Lyα nebula. Indeed, Chapman et al. (2004) speculate that a highly obscured AGN could still be responsible for a jet structure inclined well away from our line of sight that is inducing star formation with the observed spatial morphology. Ionizing flux from the AGN in such a geometry could then also assist in lighting up the Lyα cloud. The only obvious difficulty with this interpretation is the apparent absence of extended radio structure. We will return to these scenarios in the Discussion below.

2. Data and Analysis

We analyze archival data, taken with the ACIS-S detector onboard *Chandra* on 2001 July 10. The 78 ks observation was centered at $\alpha_{2000} = 22^h17^m32.40^s, \delta_{2000} = +00°13'09.9''$, well-situated for studying the Lyα blobs detected by Steidel et al. (2000) located at $\alpha_{2000} = 22^h17^m25.7^s, \delta_{2000} = +00°12'49.6''$ (B1) and $\alpha_{2000} = 22^h17^m39.0^s, \delta_{2000} = +00°13'30.1''$ (B2). Previously, these data have been analyzed by Chapman et al. (2004) (for B1) and by Bautz & Garmire (2002).

We follow the standard procedure of eliminating high background by excluding times where the counts exceeded quiescent levels. This observation was fortunate to have not occurred during any flares, and no time is excluded. Next we create the instrument map, using the CIAO `mkinstmap` command, for the ccd chip containing our data: the back-illuminated ACIS-S3. As described below, final photon counts for the detected source are very low; consequently, we determine monochromatic exposure maps in two bands (spatially binned by 4 to 2'' pixels), with the energy chosen to match the most probable photon energy in the observed counts in each band, namely, hard (2-8 keV) : 3.0 keV; and soft (0.3-2 keV): 0.8 keV. The total band map (0.3-8 keV) was formed by averaging these maps. Finally, image maps with units of photon cm^{-2} s^{-1} pixel^{-1} are constructed.

The smoothed, 0.3-8 keV X-ray image of the B2 region is compared to the Lyα image in Figure 1. There is visual evidence for correlation of the X-ray image with the Lyα image and possibly even with the extended Lyα features. The region of B1 is not apparent in any of the soft, hard (Figure 2) or total X-ray images, and the soft X-ray image does not seem to contain evidence for B2 (Figure 3). To quantify these observations we use three separate techniques. First we apply the CIAO *wavdetect* algorithm which convolves the

image with a "Mexican hat" wavelet kernel to identify sources. In both the hard image and the total image *wavdetect* finds sources coincident with the Lyα position for B2, with a signal-to-noise ratio determination of 2.7 (2-8 keV) and 3.6 (0.3-8 keV); however, *wavdetect* does not find any sources in the soft image of B2 or for B1 in any of the bands. Our second method serves to verify these results manually. In our manual test, we integrate the counts within 8″ of the source. Taking *Chandra*'s point-spread function (PSF) into account, an 8″ radius aperture conservatively contains ∼95% of the flux of a point source at 8 keV and more at lower energies. The size of this hard PSF and low signal-to-noise ratio complicates the interpretation of any possible extended nature of the B2 feature, and it is conceivable that the emission is not due to a single point source. We determine a background count by choosing an annulus surrounding our source with an inner radius of 9″ and outer radius of 25″. Our calculations of the signal-to-noise ratio are consistent with the *wavdetect* results.

A third test for the significance of the B2 X-ray counterpart is to determine the probability that the detection is a chance coincidence of X-ray emission at the B2 location. By placing 1000 random 8″ apertures throughout the field and integrating the hard and total band flux within each aperture to obtain the probability distribution of counts we determine the likelihood of the total count exceeding that obtained in the B2 region. From this Monte Carlo analysis we determine that our detection is 98% significant for the total band image, and 99% significant for the hard band image. The same test performed on the soft band yields a 90% significance, which corresponds to less than a 2 σ detection for Poissonian distributions. We therefore conclude that a hard X-ray source exists at this location and therefore may be associated with the Lyα emission, B2. However, we concede that the source is extremely faint and without the agreement of these separate tests and previous knowledge of the Lyα source, one might not consider this detection relevant; such was the conclusion reached by Bautz & Garmire (2002).

The further possibility that the X-ray source is a chance alignment of an unassociated AGN with the Lyα blob has been investigated. Using the study by Bauer et al. (2004) of X-ray number counts in the Chandra Deep Field, the number of sources per square degree with flux greater than or equal to the B2 source implies only $\simeq 0.016$ sources per 8″ aperture. We are therefore 98% confident that the X-ray source and the Lyα source are indeed related.

The background-subtracted 2-8 keV count rate within an 8″ aperture centered in B2 is $1.3(\pm1.1) \times 10^{-4}$ counts s^{-1} (24 ± 20 counts). As discussed, the rate in the soft band is indistinguishable from the background. The hardness ratio ($H-S/H+S$) for B2 is therefore consistent with unity. In order to assess the possible degree of absorption responsible for this spectral hardening we have assumed a generic, intrinsic power-law X-ray spectrum of photon index 1.4, and a measured Galactic foreground absorbing column of $n_H = 4.8 \times 10^{20}$

cm^{-2}. We then use XSPEC to determine the intrinsic luminosity and additional absorbing column (assuming solar abundances) necessary to reproduce the observed *Chandra* upper limit to the soft-band count rate and the hard-band count rate. Table 1 summarizes the resulting luminosity estimates (absorbed and unabsorbed) corresponding to observed and emitted energy bands. The required absorber column density is $\gtrsim 9 \times 10^{22}$ cm^{-2}. Assuming this best fit model we then estimate the observed 2-8 keV flux to be $2.2\pm2.0 \times 10^{-15}$ ergs cm^{-2} s^{-1}, the 0.3-2 keV 3 σ upper limit flux of 5.4×10^{-16} ergs cm^{-2} s^{-1}, and a total 0.3-8 keV flux of $2.7\pm2.0 \times 10^{-15}$ ergs cm^{-2} s^{-1}.

If the X-ray source is indeed point-like, the estimate (Table 1) for an unabsorbed X-ray luminosity of $\sim 10^{44}$ erg s^{-1} is not inconsistent with the B2 region harboring a supermassive black hole (SMBH), with a very high local absorbing column. Such a column is physically unlikely for an extended source, although the possibility remains for more than one point source associated with B2.

2.1. Upper limits on Lyα blob counterparts

Matsuda et al. (2004) have published a catalog of 35 Lyα blob candidates across the broader SSA22 field. We have examined the 12 candidates that are covered by the *Chandra* ACIS-S3 chip in the data considered here. *Wavdetect* picked out three sources that roughly matched the coordinates from the catalog, including B2. However none of these six had signal-to-noise ratio values greater than 2, except B2. Excluding B1 and B2, the remaining 10 blobs have no obvious X-ray counterparts. The published positions of the blobs are given to a precision of only 6$''$, so it is impossible to rule out all counterparts, however, there are only two cases where an X-ray source lies on the edge of a 6$''$ radius region. We have therefore stacked the X-ray data extracted in 8$''$ radius regions around these 10 Lyα sources. The Monte Carlo technique described in the previous section evaluated an 85% significance for the hard stacked data and only a 66% significance for the soft stacked data. We determined the 3σ upper limit to a mean X-ray count rate to be $\sim 8 \times 10^{-5}$ counts s^{-1} (in the observed 0.3-8 keV). This corresponds to an upper limit on the unabsorbed X-ray flux or luminosity (assuming $z = 3.09$) of $\sim 10^{-15}$ ergs cm^{-2} s^{-1} or 7×10^{43} ergs s^{-1} respectively.

3. Summary and Discussion

The evidence presented above for the presence of obscured AGN emission of $L_x \sim 10^{44}$ erg s^{-1} embedded in the Lyα cloud/B2 of SSA22 provides the first direct indication of AGN

activity in this possibly unusual, radio-quiet, object. This detection provides significant clues as to what is going on in its "companion" Lyα cloud, B1, and possibly to the generation of the Lyα cloud emission itself.

It is useful to compare and contrast B1 and B2. These objects have comparable Lyα luminosities, both are detected in the submillimeter, while B2 is a factor of ~ 10 less luminous, and while B2 has an X-ray detectable, albeit highly obscured, AGN, B1 does not to the current sensitivity limits.

Various scenarios can be constructed from these observations. For example, *if* the observed submillimeter luminosity is directly indicative of the mass of dust in a system (assuming similar temperatures) then it is tempting to conclude that B2 is less enshrouded than B1 and is therefore more transparent to high-energy X-rays (8-33 keV rest frame). While this may be correct, it is also possible that the obscuration of the AGN (in B2 for certain) is due to a much smaller scale molecular/dust torus surrounding the SMBH. The similarity in Lyα luminosity is intriguing. If the ionizing source for the Lyα cloud were directly connected with that responsible for heating the submillimeter dust (i.e. starburst activity) then some amount of coincidental tuning would be needed to produce a similar level of emission between B1 and B2.

Finally, we offer a different, albeit speculative, mechanism that could explain many, if not all, of the above features of the B1 and B2 systems. Recently, evidence has been found for extended X-ray emission around high-z radio-loud galaxies due to the inverse Compton scattering of cosmic microwave background (CMB) photons by a population of relativistic particles originating from the central SMBH in these objects (Fabian, Sanders, Crawford, & Ettori 2003; Scharf et al. 2003). Owing to the $(1 + z)^4$ growth of the CMB energy density, this emission is increasingly luminous at high-z, and can readily exceed that of the central AGN (Schwartz 2002; Scharf et al. 2003). In at least one case (Fabian, Sanders, Crawford, & Ettori 2003), much of the X-ray emission appears to be due to an *older* relativistic population of much greater spatial extent than the currently detected radio synchrotron emission. The presence of a spatially extended, highly luminous, X-ray emission offers a ready mechanism for photo-ionization of cooler gas. Indeed, Scharf et al. (2003) speculate that it alone could sustain a ~ 100 kpc Lyα emission cloud, while not over-ionizing observed species such as those of oxygen. If B2 (and perhaps B1) contains an AGN, then it is plausible that a population of older relativistic particles exist on scales of ~ 100 kpc, unseen via radio synchrotron since the typical emission frequencies will be less than 100 MHz (rest frame) but still actively upscattering CMB photons to the X-ray. Some of the "triangular shaped" or hourglass, morphology of the Lyα clouds reported in B1 (Chapman et al. 2004) and seen in B2 (Steidel et al. 2000) matches extremely well the morphologies seen in the X-ray

surrounding 3C 294 ($z = 1.89$; Fabian, Sanders, Crawford, & Ettori (2003)) and in *both* the X-ray and Lyα seen in 4C 41.17 ($z = 3.79$; Scharf et al. (2003)). The relatively low X-ray surface brightness of such emission ($\sim 8 \times 10^{-17}$ ergs s^{-1} cm^{-2} arcsec^{-2}) would indicate that it can readily escape direct detection even in a 78 ks ACIS-S observation - although as discussed in Section 2, there is some suggestion that the B2 X-ray emission could be extended. The phenomenon described above offers an interpretation if this is the case.

In such a picture, the relative submillimeter, radio, and optical luminosities associated with the Lyα clouds are essentially decoupled from the mechanism responsible for exciting their fluorescent emission - which is driven by a periodic injection of relativistic particles (as seems to be a standard AGN property), and the enhanced energy density of the CMB (a factor of 280 at $z = 3.09$).

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Table 1.   Estimated absorbed and unabsorbed X-ray model luminosities in *rest frame* energy ranges (E_{em}) for B2 (corresponding observed energy ranges given under E_{obs}.)

E_{em} (keV)	E_{obs} (keV)	L_{abs}[a] (10^{44} ergs/s)	L_{unabs} (10^{44} ergs/s)
2−8	0.5−2	0.46 *	0.87*
0.3−2	0.08−0.5	0.00047*	0.42*
0.3−8	0.08−2	0.46*	1.3*
1.2−8	0.3−2	0.46*	1.0*
8−33	2−8	1.9±1.6	2.0±1.7
1.2−33	0.3−8	2.3±1.7	3.1±2.2

*These are upper limits.

[a]uminosities were calculated using the following cosmology: $H_0 = 71$ km s^{-1}Mpc^{-1}, Ω_M=0.270, Ω_ν= 0.730

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